

High energy cosmic electrons: messengers from nearby cosmic ray sources or dark matter?

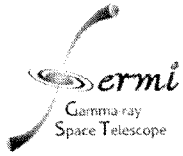
Alexander Moiseev

***NASA Goddard Space Flight Center and
CRESST / University of Maryland***

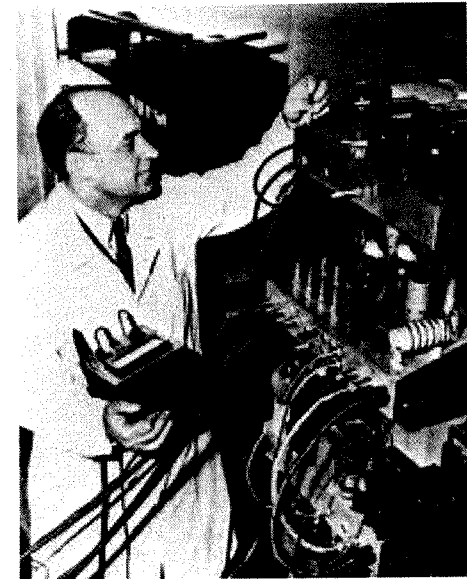
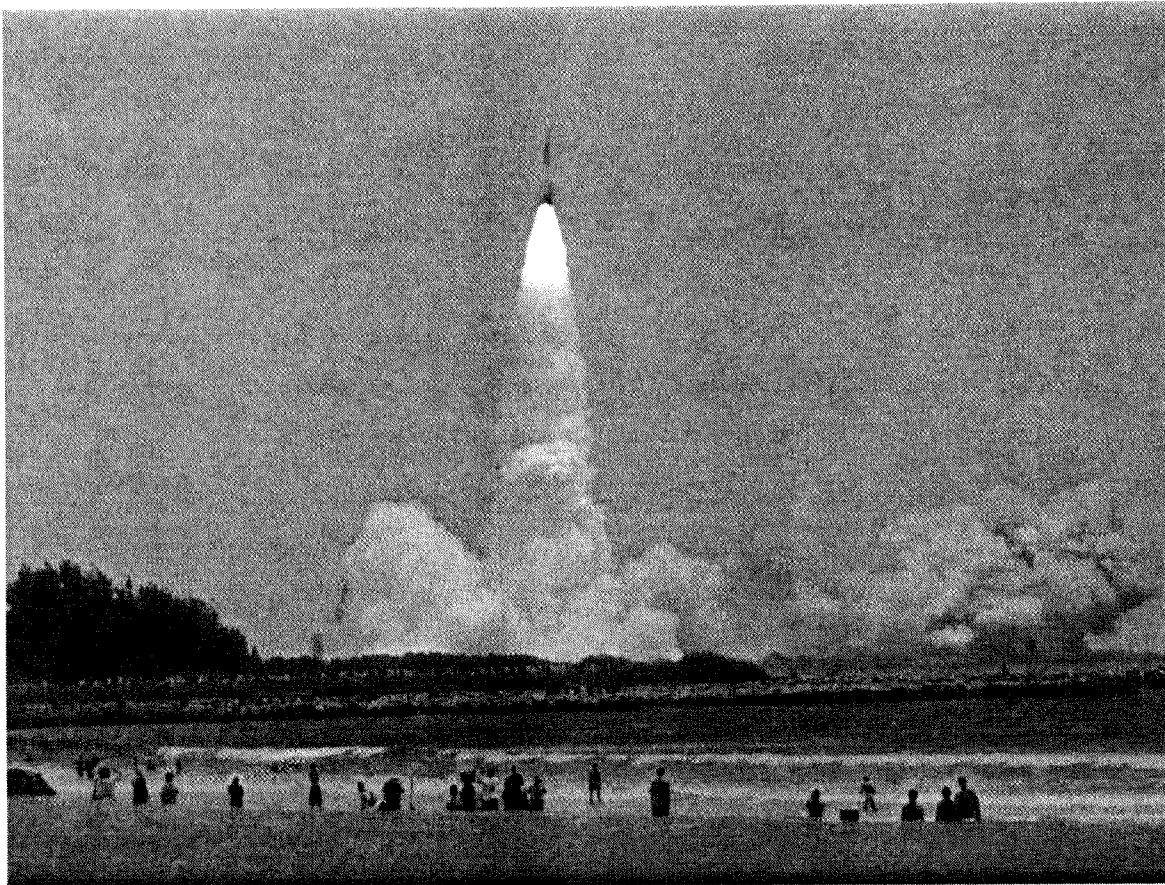
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Fermi Gamma-ray Space Telescope was launched on June 11, 2008



1901 – 1954

...

...

2008 -

"There are two possible outcomes: If the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery." Enrico Fermi

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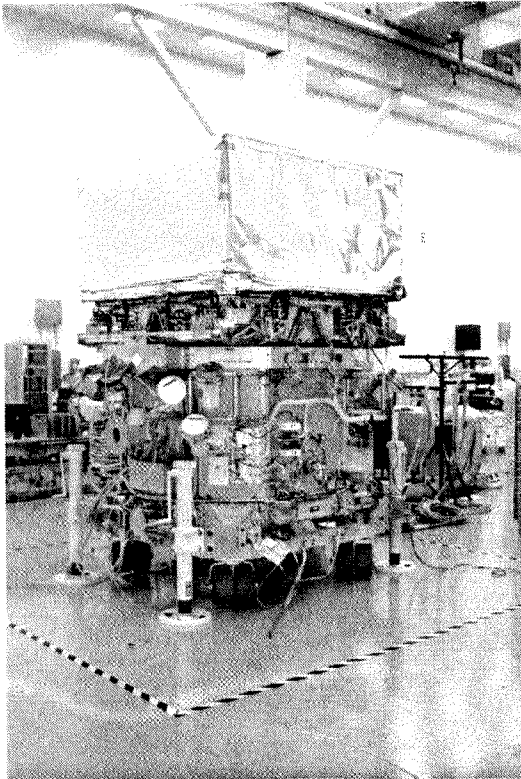
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The Fermi Gamma-Ray Space Telescope

- **Large Area Telescope (LAT)**
(20 MeV – >300 GeV)
- **Gamma-ray Burst Monitor (GBM)**
(8 keV – 40 MeV)



***Spacecraft with LAT and GBM
before shipping to KSC***

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LAT collaboration

France

- ✧ IN2P3/LLR Ecole Polytechnique
- ✧ IN2P3/CENBG Bordeaux
- ✧ IN2P3/LPTA Montpellier
- ✧ CEA/Saclay
- ✧ CESR Toulouse



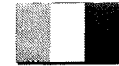
Germany

- ✧ MPI fuer extraterrestr. Physik, Garching



Italy

- ✧ INFN Bari, Padova, Perugia, Pisa, Rome, Trieste, Udine
- ✧ ASI
- ✧ INAF-IASF



Japan

- ✧ Hiroshima University
- ✧ ISAS/JAXA
- ✧ Tokyo Institute of Technology



Spain

- ✧ IEEC-CISC, Barcelona



Sweden

- ✧ Royal Institute of Technology (KTH)
- ✧ Stockholm University



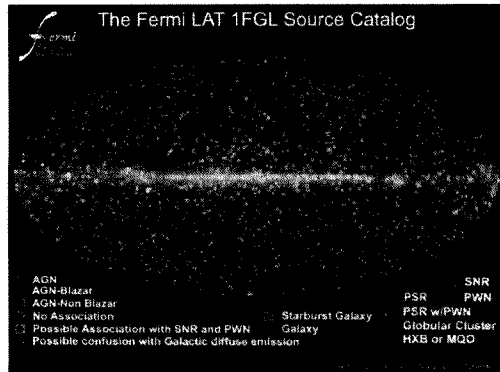
United States

- ✧ Stanford University (HEPL/Physics, SLAC, KIPAC)
- ✧ UC Santa Cruz
- ✧ Goddard Space Flight Center
- ✧ Naval Research Laboratory
- ✧ Sonoma State University
- ✧ Ohio State University
- ✧ University of Washington
- ✧ University of Denver
- ✧ Purdue University – Calumet

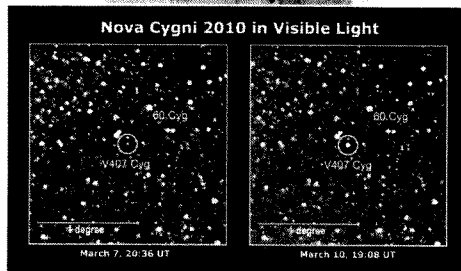
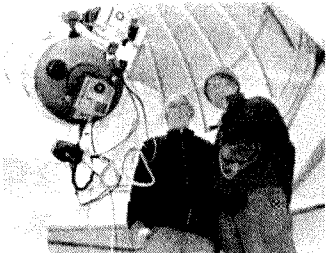




Fermi LAT science objectives cover practically all aspects in astrophysics

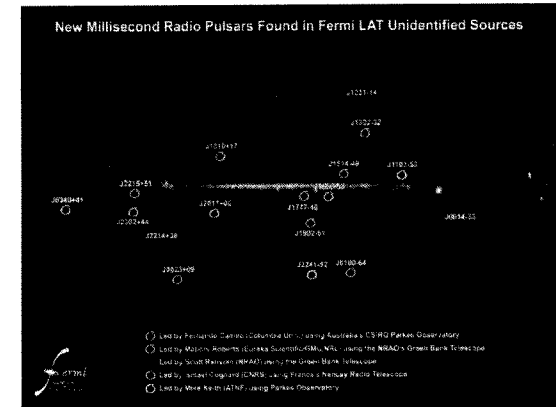


First Fermi source catalog (1,451 source)

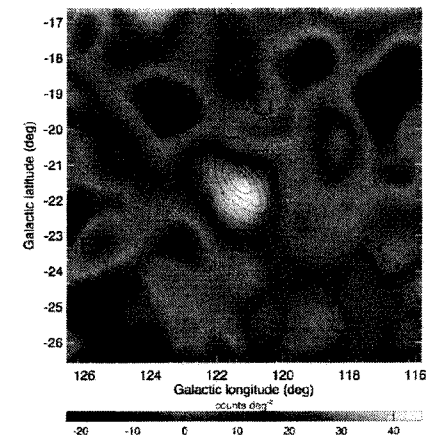


Gamma-signal from Nova Cygni

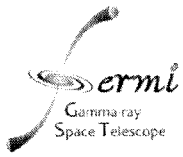
- Active galactic nuclei
- Gamma ray bursts
- Supernova remnants
- Pulsars
- Solar system objects
- Galaxies, clusters of galaxies, X-ray binaries
- Unidentified sources/new populations
- Diffuse gamma-ray emission
- Cosmic-ray acceleration & propagation
- Extra-galactic background light (EBL)
- Search for Particle Dark matter
- Tests of new physics



Milliseconds Pulsars



Detection of gamma-signal from M31 Andromeda



Fermi results recognized as one of the top 10 science breakthroughs of 2009 (Science, December 2009)



Many discoveries in different topics. Fermi LAT Collaboration just has published its 117-th paper (~ 2,500 citations to date). 6 more are in press and 20 have been submitted

Each of these paper is a complete high-level analysis covering one of the topics listed above.

It is impossible to address all of them in one talk!

***I will briefly go through the main results.
Please do not hesitate to ask me for the details
off line***

Why electrons?

- Due to their low mass high energy cosmic ray electrons (CRE) lose their energy rapidly (as $-dE/dt \sim E^2$) by synchrotron radiation on Galactic magnetic fields ($\approx 3\text{-}6 \mu\text{G}$) and by inverse Compton scattering on the interstellar radiation field (starlight and 2.7 K CMB , $\approx 1 \text{ eV/cm}^3$)

- The life-time of CRE due to these energy losses is

$$t = E / (-dE / dt) \approx 3 \times 10^8 (E / 1 \text{ GeV})^{-1} \text{ yr} \Rightarrow \text{age of CRE observed at 1}$$

TeV is $\sim 10^5 \text{ yr}$

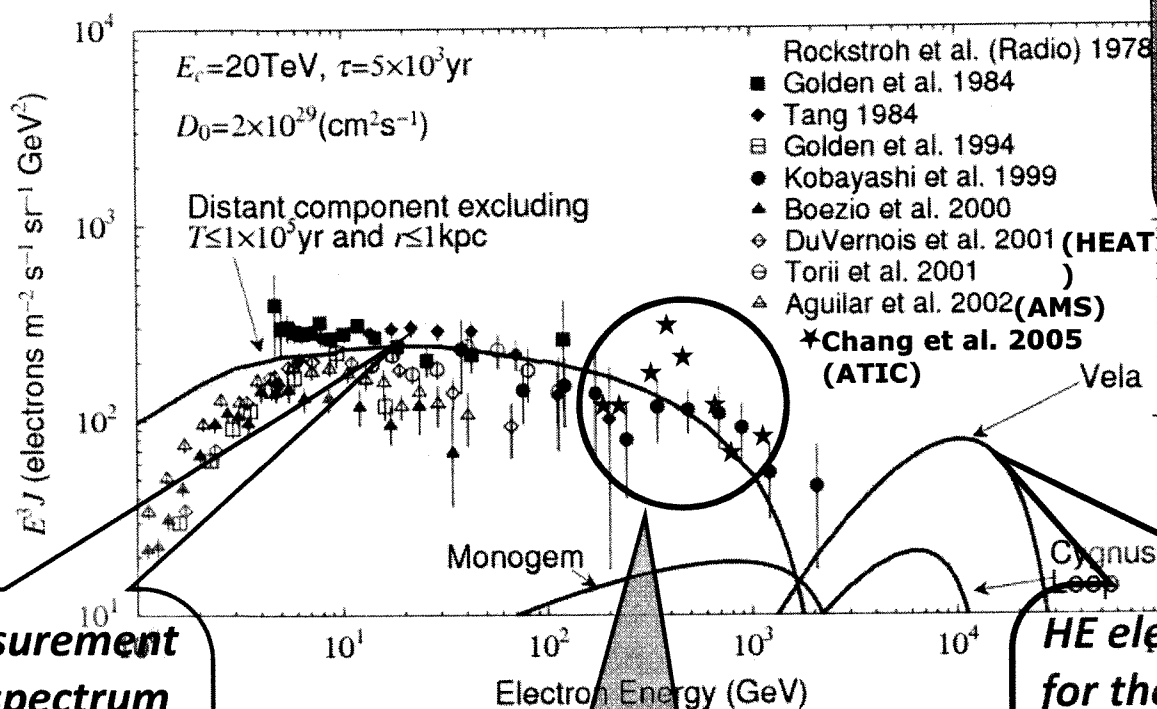
- The typical distance over which a 1 TeV CRE loses half of its energy is $\sim 300\text{-}400 \text{ pc}$

- Observation of such HE CRE would imply existence of a nearby source of TeV electrons

- This makes CRE a unique tool for probing nearby Galactic space (Galactic halo is $\sim 40 \text{ kpc}$ diameter, $\sim 4 \text{ kpc}$ thick)

What can be learned from HE electrons ($E > 10$ GeV) ?

As we realized it in
2006



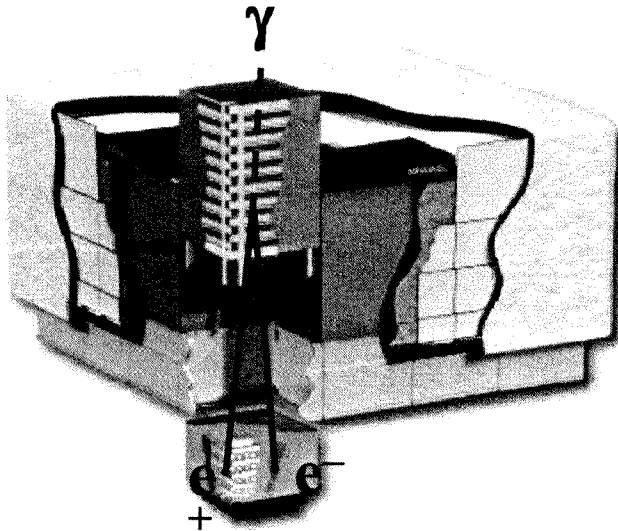
Search for
anisotropy in HE
electron flux :
nearby sources,
streaming of local
magnetic fields?

Precise measurement
of electron spectrum
above 10 GeV
(CR diffusion model;
IC gamma ray flux
model calibration,
GALPROP)

Search for Dark
Matter Signatures

HE electrons origin: Search
for the signature of nearby
HE electrons sources
(believed to be SNR) in the
electron spectrum above ~
TeV

LAT as a detector of high energy cosmic ray electrons



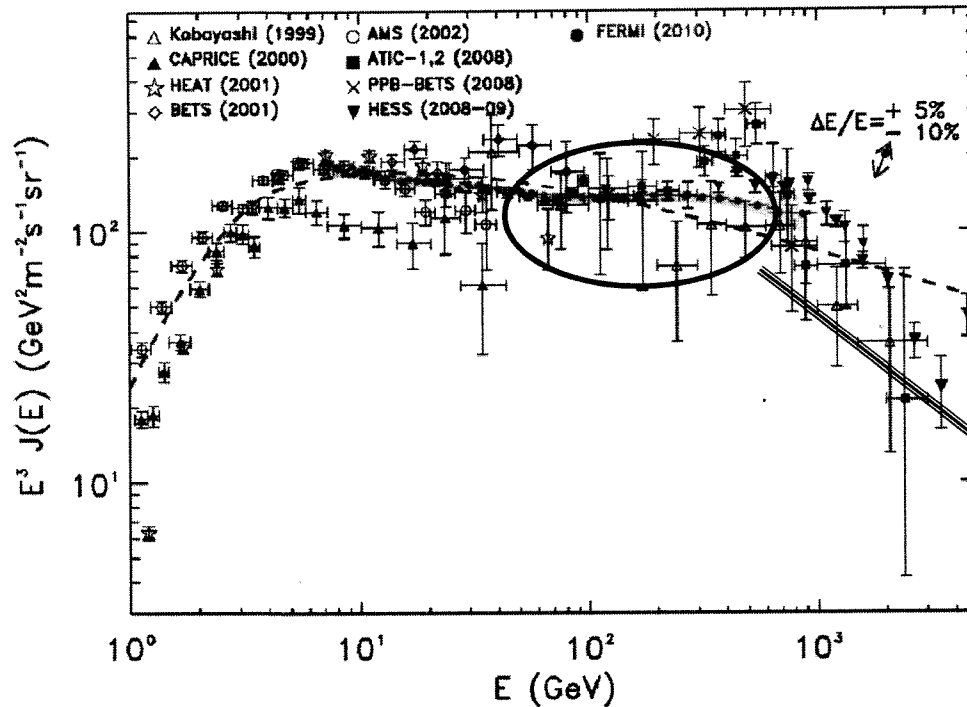
- The LAT is composed of a 4x4 array of identical towers. Each tower has a Tracker and a Calorimeter module. Entire LAT is covered by segmented Anti-Coincidence Detector (ACD)
- Although the LAT was designed to detect photons, it was recognized early in its design that the LAT is a capable detector of high energy electrons too

- The electron data analysis is based on that developed for photons. The main challenge is to identify and separate electrons from all other charged species, mainly CR protons (for gamma-ray analysis this is provided by the Anti-Coincidence Detector)
- The hadron rejection power must be $10^3 - 10^4$ increasing with energy
- Another challenge – assessment of systematic errors : statistical errors will be very small

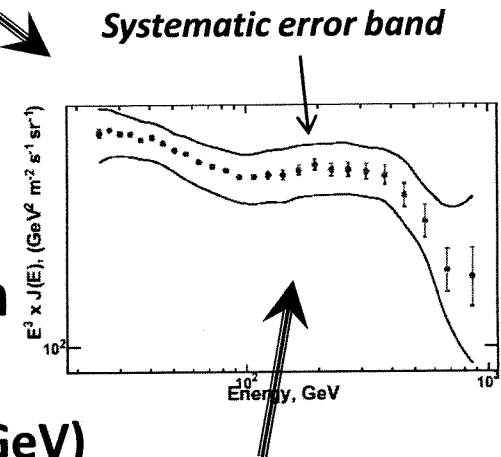


Fermi LAT electron+positron spectrum 7 GeV – 1 TeV

Ackerman et al., Fermi LAT Collaboration, Phys. Rev. D82, 092004, November 2010 (arXiv 1008.3999)



Our first results were published in PRL 102, 181101, 2009. It is the most cited Fermi LAT paper so far (over 400 times)



Data collected for the first 12 months of operation

- Total statistics 7.95 M electron candidate events
- More than 1000 events in highest energy bin (772 – 1000 GeV)

Noticeable deviation from single power law spectrum



CR Electrons Anisotropy

Ackermann et al., Fermi LAT Collaboration, Phys Rev D82, 092003, November 2010 (arXiv 1008.5119)

Search for CR electrons anisotropy can provide information on:

- **Local CR sources and their distribution in space**
- **propagation environment**
- **heliospheric effects**
- **presence of dark matter clumps producing $e^+ e^-$**

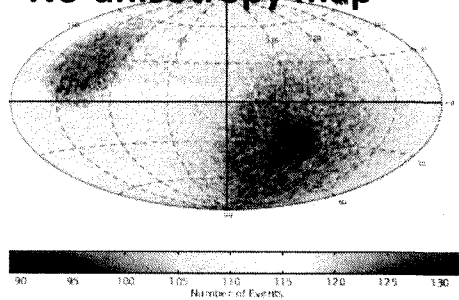
Due to its large statistics and high angular resolution, the Fermi LAT is very capable for such study

Approach:

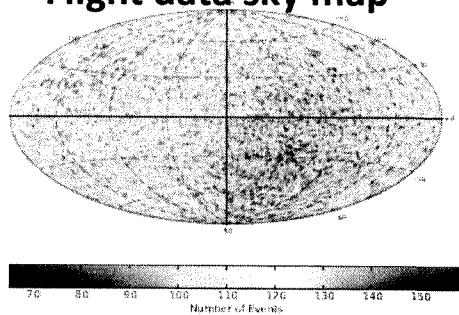
- **statistical comparison of “no anisotropy” sky map of electron counts with the flight data. Energy from 60 GeV to ~600 GeV**
- **“no anisotropy” sky map is made of the flight data by either randomizing the reconstructed directions of the detected events**
- **analysis is performed in several energy intervals by either direct bin-to-bin comparison or by spherical harmonic analysis**

CR Electrons Anisotropy (cont.)

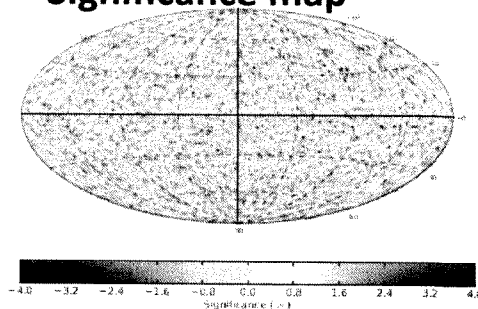
No-anisotropy map



Flight data sky map

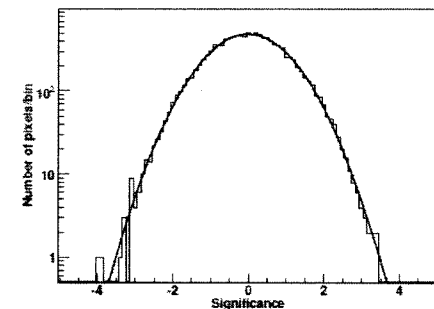


Significance map



Result:

- More than 1.6 million electron events with energy above 60 GeV have been analyzed on anisotropy
- Upper limit for the dipole anisotropy has been set to 0.5 – 5% (depending on the energy)
- Upper limit on fractional anisotropic excess ranges from a fraction to about one percent (depending on the minimum energy and the anisotropy's angular scale)
- Our upper limits lie roughly on or above the predicted anisotropies



Distribution of significance, fitted by a Gaussian

Interpretation

D. Grasso et al., *AstroPart Physics* 32 (2009), 140

Task: find a model which agrees with all relevant experimental results

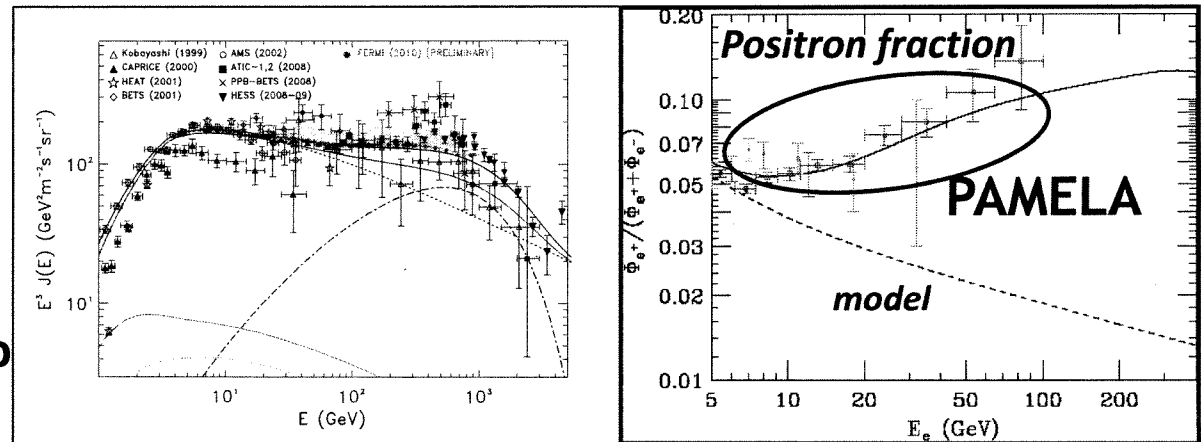
Inputs:

- **Results**

- ✓ Fermi $e^+ + e^-$ spectrum
- ✓ HESS $e^+ + e^-$ spectrum
- ✓ Pamela e^- spectrum
- ✓ Pamela $e^+/(e^+ + e^-)$ ratio
- ✓ Pamela p^+ spectrum

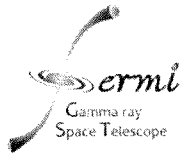
- **Models**

- ✓ diffusion propagation (plain, Kolmogorov, Kraichman)
- ✓ solar modulation
- ✓ single vs. additional (several) components in the electron flux



Conventional model: $e^+ + e^-$ spectrum consists of dominating “primary” (produced in quasi-uniformly distributed distant astrophysical sources, thought to be SNR) e^- , plus contribution from “secondary” e^+ and e^- , produced in interactions of cosmic rays with interstellar matter

Additional component: it is assumed that there is a source of HE $e^+ + e^-$ with hard spectrum



Interpretation (cont.)

Fermi - LAT:

- We were rather successful to fit our first spectrum published in PRL paper (20 GeV – 1 TeV) with a single component (single power law fit).
- With our new spectrum extended down to 7 GeV we tested many combinations of injection spectra, diffusion models and solar modulation. It appears that the spectral flattening at 20-100 GeV and the softening at ~ 500 GeV cannot be satisfactorily fitted by the single component model.
- Most important, the Fermi LAT spectral slope between 7 and 100 GeV cannot be reproduced

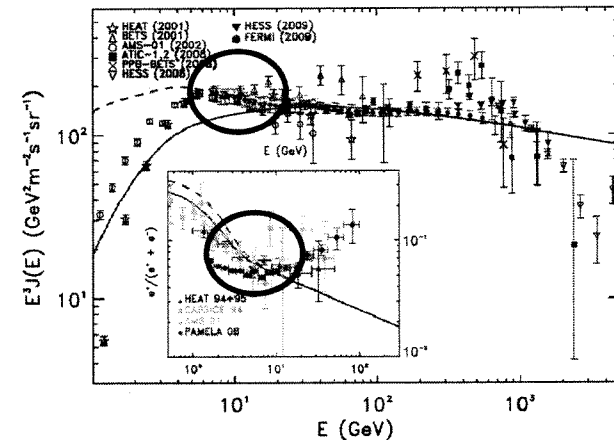
Pamela:

- Positron fraction cannot be reproduced as well

Conclusion: new Fermi LAT electron spectrum cannot be explained within conventional single-component model

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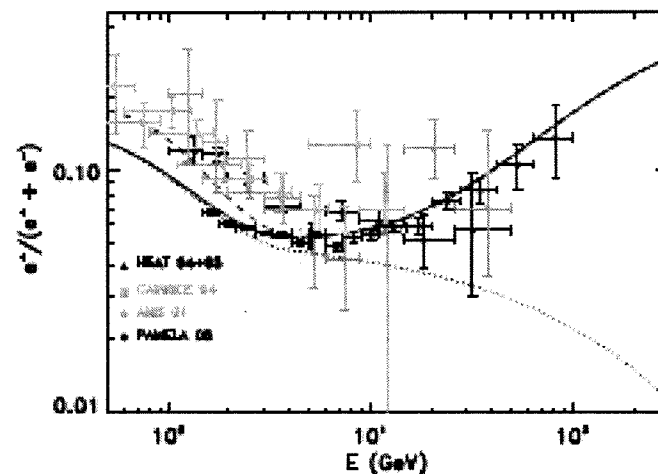
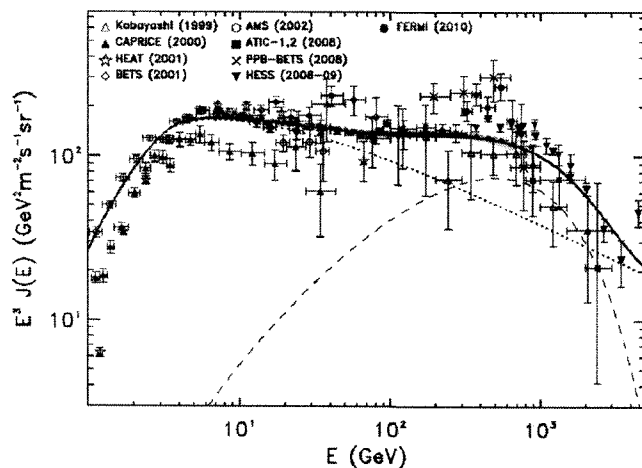
For details see D. Grasso, talk in Galileo Galilei Institute
<http://www.ggi.fi.infn.it/talks/talk1547.pdf>. Paper is in preparation

Interpretation (cont.)

Now we introduce an additional component of the CRE flux.

It is assumed that the additional source (can be astrophysical or “exotic”, such as dark matter clump) provides equal amount of e^+ and e^- , in order to satisfy Pamela positron ratio.

Important to notice that though the new extended Fermi LAT spectrum needs an additional hard spectrum source, it does not have to be e^+ and e^- ; only e^- suffice



Fit of Fermi LAT and Pamela data with 2-component model. Standard component: injection spectral index 2.0/2.65 above/below 4 GeV and $E_{\text{cut}} = 3$ TeV. Additional component with spectral index 1.5 and $E_{\text{cut}} = 1.4$ TeV. Solar modulation parameter $\Phi = 550$ MV



Why are the $e^+ e^-$ sources not seen at lower energy, where the positron fraction agrees with their pure secondary origin (CR interactions with ISM) ?

What could be the origin of the e^+e^- hard spectrum?

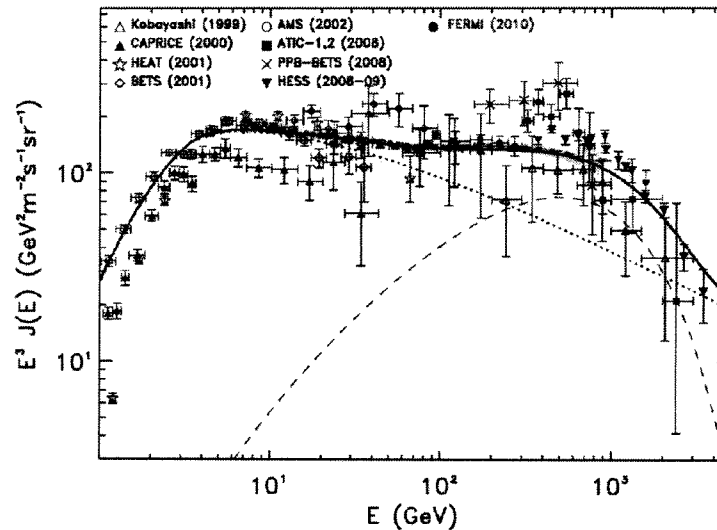
There are several models, including acceleration of “secondary” e^+ and e^- in the CR acceleration regions (Blasi 2009), consideration of Klein-Nishina suppression of energy losses near the points of origin (Aharonian & Atoyan 1991, Stawarz et al. 2009), enhanced e^+e^- acceleration in pulsar polar cap (Biermann et al. 2009)

Multiple cascading in pulsar magnetosphere can also provide needed acceleration of e^+e^-

Promising sources of high energy pairs could be MSP (with many discovered by Fermi) due to their high rotation frequency and low surface magnetic field (low energy losses).

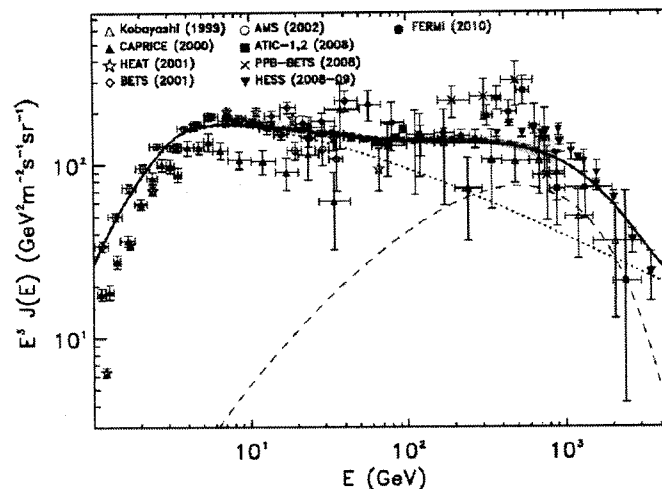
Dark matter origin of these sources is not excluded

Summary



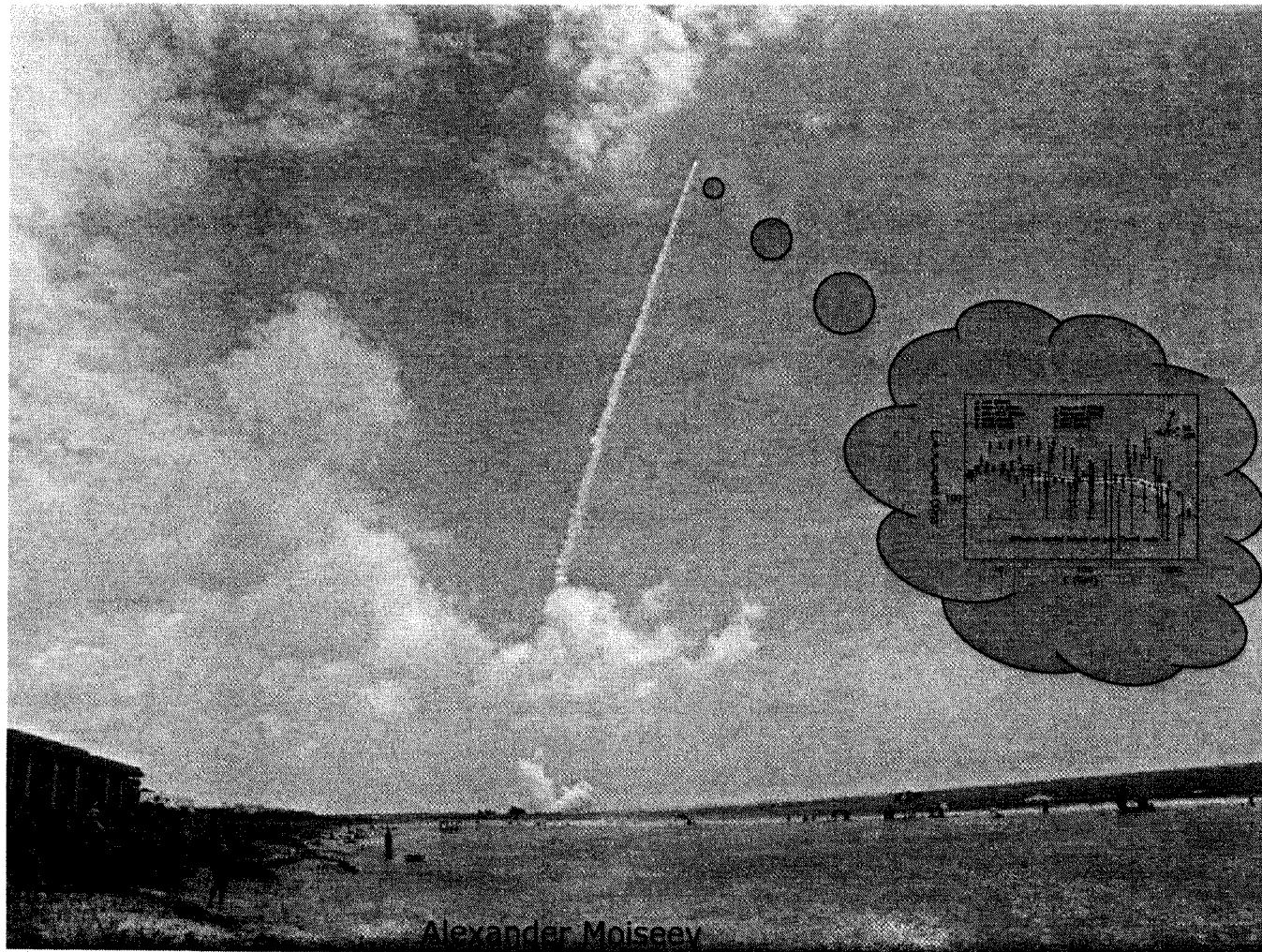
- Real breakthrough during last 1-1.5 years in cosmic ray electrons: ATIC, HESS, Pamela, and finally Fermi-LAT. New quality data have made it possible to start quantitative modeling.
- Now we can discuss not only the origin of CR electrons, but also constraints of their source(s) models based on new results.
- No good fit with a pre-Fermi conventional model to satisfy both Fermi and Pamela
- Introduction of an additional hard component provides a good fit of the Fermi LAT spectrum. It is viable that we are dealing with at least two distinct mechanisms of “primary” electron (both signs) production.

Summary (cont.)



- To satisfy the Fermi LAT spectrum, this component can comprise e^- only , but Pamela result requires e^+e^- pairs.
- Nature of such a component is still a question. Can be astrophysical (e.g. pulsar systems), exotic (DM), or other effects
- Our upper limits on anisotropy can be used to constrain the models of the sources and propagation
- Critical new results on the positron fraction are expected from the AMS.
- With the new data more puzzles than before; need “multi-messenger” campaign: electrons, positrons, gammas, X-ray, radio, neutrino...

THANK YOU !



April 5, 2011

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